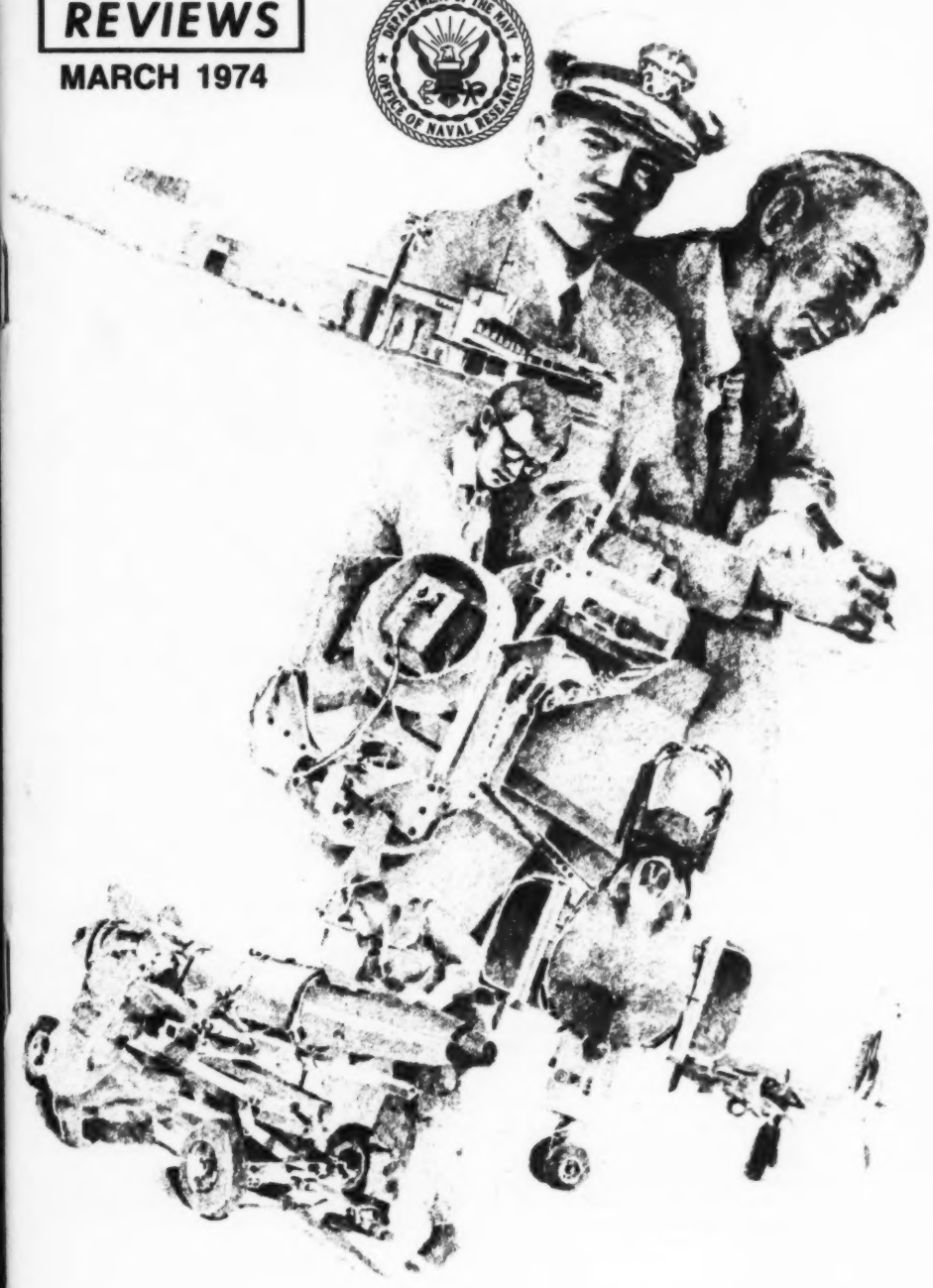
U.S.7 N56r3
v.22 no.3

Sociology & Economics
Detroit Public Library SE

NAVAL RESEARCH

REVIEWS

MARCH 1974



PROFILES IN SCIENCE

Dr. Thompson

Through a half century of service and close association with the Navy, Dr. L. T. E. Thompson has had a profound influence on weapon research and development. His first involvement in ordnance was in World War I research for the Naval Consulting Board, done at the Ballistics Institute at Clark University. After receiving his Ph.D. from Clark, Thompson taught physics there and later at Kalamazoo College. In 1923 he became Chief Scientist at the Naval Proving Ground, Dahlgren, Virginia (now Naval Weapons Laboratory). He held this position, the first of its type in the Navy, for 19 years. His leadership there led to the building of the Armor and Projectile Laboratory, the first of three Navy laboratories whose development he would influence. In 1945 he became director of research for Carl Norden Corp., where he led the development of what was to become the Naval Ordnance Plant, Indianapolis. In early 1945 he developed, under contract, plans for the postwar organization of the Naval Ordnance Test Station (now Naval Weapons Center) and later in the year was made the Station's first Technical Director. He formulated much of the weapon research and development philosophy that still characterizes the work of NWC. Under his leadership, development of the Station's Michelson Laboratory was successfully concluded. Thompson returned to Norden Corp. in 1952 as its vice president. Since leaving Norden in 1958, Thompson has continued to influence military scientific policy as a scientific consultant and advisor to numerous agencies.

The Naval Weapons Center, A Multifaceted Research and Development Environment*

An activity of the Naval Material Command, the Naval Weapons Center has the people, facilities, and equipment necessary to pursue the complete spectrum of ordnance research, design, development, fabrication, and testing, all within its boundaries. The Center is the principal Navy RDT&E center for air warfare and missile weapon systems.

What is the Navy doing on the desert? Previous to 1943 Indian Wells Valley was a huge vacant area of California's Mojave Desert. Nomadic Indian tribes had passed through here, foraging for a precarious existence. Prospectors had sunk numerous mine shafts, searching for gold and other precious metals, and a few hardy homesteaders had scratched a living from the arid soil. Death Valley '49ers had passed through this valley, as had stagecoaches enroute between Los Angeles, 150 miles to the south, and the fabled Cerro Gordo mine in the mountains above Owens Valley to the north.

The story of the Navy's involvement with this remote piece of California real estate melds two entities–the military establishment and the scientific research community. The proposal in 1943 to locate an ordnance test station in the Indian Wells Valley was motivated by two separate, but compatible, arguments from two separate sources, one scientific and the other military.

Dr. Charles C. Lauritsen, the nuclear physicist in charge of the wartime rocket development program of the California Institute of Technology, urgently needed more space for rocket testing. Commander (now Rear Admiral) Sherman E. Burroughs, Jr., recently returned from aerial combat duty in the Pacific, felt the Navy urgently needed a center for developing better aircraft ordnance. Lauritsen and Burroughs agreed that both objectives could be met at one place.

Rear Admiral William H. P. Blandy, Chief of the Navy's Bureau of Ordnance recognized the validity of Lauritsen's and Burroughs' needs. Further, he had some ideas of his own, motivated by his strong belief in the importance of science to the advancement of ordnance. Although the end of the bloodiest war in human history

*This issue of the *Naval Research Reviews* was organized by the Technical Information Department of the Naval Weapons Center and this article was prepared by Elizabeth Babcock, an employee of that department.

was not in sight, Blandy's attention was increasingly turning to plans for a peacetime Navy in which the wartime technological gains would not be lost. He recognized the profound revolution that scientific research had brought to naval armament in the wartime environment. If scientific expertise within the Navy could be built up before the cessation of hostilities, a foundation would be laid for a continuous system of military/scientific collaboration. He saw in the proposal for a station for rocket testing and aircraft ordnance development the opportunity to prepare the way for a permanent research and development center for naval ordnance.

The Blandy influence is apparent in the order that established the forerunner of the Naval Weapons Center, the Naval Ordnance Test Station (NOTS), on November 8, 1943. It stated that the primary function of the new Station was to be "the research, development, and testing of weapons . . ."

In actuality there would be no research and little development at NOTS until the end of the war when the weapon development projects of CalTech were transferred to NOTS and a research staff was recruited. But in accordance with Blandy's plan much work was done during the war in the development of facilities and plans for the permanent R&D center.

Quite as important to the future of this new Navy installation was the close and highly effective working relationship that came into being between NOTS wartime military personnel and the CalTech scientists. Thus the foundation was laid for the military/civilian cooperative effort that is a chief characteristic of NWC today.

NOTS In World War II

Under the vigorous leadership of Burroughs, NOTS' first Commander, the new Station rapidly came into being. Less than a month after the order establishing NOTS, test operations were under way. In less than 2 years, a complex of ranges, a headquarters, two air facilities, a community, a pilot plant for propellants, and a pilot plant for atomic bomb explosive components were built.

Although the first plans had given the "village" secondary consideration out of concern for the urgency of the test operations, it became apparent as the permanent technical facilities were planned that permanent housing was also required. It was felt that quality housing and good living conditions were essential to attract and hold the top scientists and engineers required for the Station's mission. The same rationale led to the construction of a complete shopping and recreation center at the heart of the China Lake Community. A post office, commissary, bank, and a variety of shops were built, as well as a gymnasium and indoor swimming pool for the use of all employees and their families.

During the wartime years, NOTS carried out test, training, and experimental production operations in support of the CalTech rocket program. Rocket propellant grains were extruded at the new China Lake Pilot Plan, built on the shoulder of a nearby mountain, at a good location for both open space and nearness to the testing area. The first tests conducted on NOTS ranges were of the 3.5-inch rocket. CalTech developed this small aircraft rocket for antisubmarine use; the promise of this new weapon had been instrumental in justifying NOTS' establishment. Also developed and tested was the Holy Moses HVAR (5-inch high-velocity aircraft rocket), an effective World War II weapon later used in the Korean conflict. With these and other rocket programs, NOTS supported CalTech throughout the rest of the war in bringing rockets from an experimental stage to massively employed combat weapons that greatly changed warfare.

As the trend of the war became apparent by late 1944, military and civilian leaders began to think more of the postwar future for NOTS. Having witnessed the nation's traditional peacetime disinterest in ordnance experimental facilities, they were concerned that a promising new idea might be abandoned with the coming of peace.

In late June 1945 Vice Admiral George F. Hussey, chief of BuOrd, sent Burroughs a memo that clearly encouraged future investment in research. The memo stated, in part, "There is no doubt that the great success which has resulted from exploitation of science in this war is a direct consequence of the mobilization of the ablest research scientists and engineers. It is particularly significant that many of the new weapons developed during the war were based on recent work of laboratories of science, which only a few years ago had the status of projects in 'pure' science." For NOTS to make best use of its potential, Hussey continued, "it is essential to maintain a liberal atmosphere, encouraging to independent initiative . . ."

New Principles

The end of World War II marked the end of NOTS' role as a support facility for CalTech and the beginning of its operation as a naval RDT&E center. The chief architect of the NOTS postwar organization and its philosophy was Dr. L. T. E. Thompson. Thompson came on contract to NOTS to draw up plans while the war was still in progress, then stayed to become the Station's first Technical Director. He was eminently suited for this job: as Chief Scientist at the Naval Proving Ground in Dahlgren, Va., he had been influential in ballistics R&D since 1923. As a scientist uniquely familiar with the needs of the Navy in ordnance, he was aware of

past deficiencies in bringing the talents of the scientific community to bear on ordnance problems. And, as a civilian who had worked within a military framework, he was aware of pitfalls to avoid in this new military/civilian partnership.

Thompson's major contribution, both in the original organizational plan and in his later work as the Station's first Technical Director, was to develop the concept of a military/scientific management team for NOTS. This top management organizational structure, still functioning effectively at NWC, gives the Commander, a high-ranking naval officer, responsibility for all phases of operation. He delegates to the Technical Director, a civilian senior scientist or engineer, authority over all technical programs. The Commander and the Technical Director are jointly responsible for policy matters affecting the Center. This system offered then as it does today a dual advantage: immediate responsiveness to Fleet needs, as well as maximum freedom for creative scientists and engineers to function effectively. Thompson used his considerable authority to ensure that this military/civilian team could function in a single integrated organization where the whole process of weapon development could be accomplished—from idea through all the steps to Fleet introduction.

Thompson's plan would not be considered unique today, but at the time it raised skepticism by those who did not believe there could be any reasonable, workable compromise between scientific freedom and military control. Dr. Vannevar Bush, who headed the mobilization of American science during the war commented crisply on Thompson's plan. "I think they may be attempting the impossible, but we certainly will not refuse to aid on that account," Bush noted in response to Thompson's March 1945 memo detailing preliminary organization and operation of research, development, and testing at NOTS. This memo stressed a military and civilian cooperative effort "to gain the full advantage of the scientific approach to ordnance problems which has been so successful in this war."

Thompson's belief in the scientific approach to ordnance problems had served him well over years of applying his knowledge to reach practical solutions. He believed too in encouraging freedom of independent thought. One of the major advantages he saw to pursuing entire programs from conception to completion in a single integrated organization was the resulting operation of a cycle that he called the "stirring up operation." To Thompson this cycle included many kinds of thinkers, from pragmatic engineers to pure scientists. He described this process to a meeting of NOTS senior personnel in August 1951, explaining that "the development and test people need the stimulation that comes from the research for

new ideas, new approaches. They may not be actually doing the work themselves, but they are in contact, they are in the atmosphere, and they get stirred up once in a while when somebody touches something that shows up in the research laboratory . . . So what I'm trying to say is, it's a good thing not only for the development and test people to be near a research activity, but it's also good for research people to be near a development and test activity. There is a regenerative effect in the stimulation of everyone concerned."

It was not easy to achieve this integrated organization. In April 1945 construction work on NOTS' principal R&D laboratory (to be named Michelson Laboratory) came to a temporary halt while it was debated whether to relocate the laboratory near Pasadena, where ordnance research was already going on and where it might be easier to recruit high-caliber scientific personnel, or whether to continue building at China Lake. Thompson and other supporters of the China Lake site argued successfully that a 160-mile separation between the research laboratory and its test facilities would result in communication gaps, development delays, and adverse effects on NOTS products.

Michelson Laboratory was completed and dedicated in 1948. In a very real sense, this massive, completely equipped R&D structure was a strong testimony to the scientific community that the Navy was going ahead with an aggressive scientific program backed up with first-class laboratory facilities (Figure 1).

Postwar Work At NOTS

Postwar national efforts to compartmentalize military research made it appear for a while that NOTS would continue primarily in its wartime role as a rocket station. Since the Station's wartime reputation had been made in rocketry, national leaders planned to continue that work at NOTS and to use the Station's extensive facilities for missile testing. Test programs were conducted at NOTS on the early missiles Lark and Bumblebee, work on the latter leading eventually to Talos, Terrier, and Tartar. But NOTS was not assigned R&D funds for guided missiles.

Despite this lack of funding for guided missile research, the Station, with the encouragement of such Bureau of Ordnance officers as Rear Admiral William S. Parsons, proceeded with research on a "fire-control" system designed by Dr. William B. McLean (later NOTS Technical Director from 1954 to 1967). This work led in time to the famous Sidewinder, the nation's first passive

Figure 1—The China Lake community. Tree-covered housing areas are close to many of NWC's technical facilities, including Michelson Laboratory (left center).

infrared-homing air-to-air guided missile. Sidewinder was released to the Fleet in its first version in 1956. Recent NWC developments still literally pick Sidewinder's brains, with many modifications and improvements on the basic Sidewinder idea (Figure 2).

During the period following World War II, the Station continued its leadership in rocketry, as well, with a number of programs instituted by CalTech becoming follow-on programs for NOTS. The search for a smaller air-to-air rocket led to the development of a major NOTS project, the FFAR (2.75-inch folding-fin aircraft rocket), nicknamed the Mighty Mouse. Millions of FFAR rockets were manufactured during the Korean conflict, where they proved to be as effective in air-to-ground operations as they were in air-to-air. Another project led to development of the HPAG (high-performance air-to-ground rocket), resulting from improvements made to the HVAR; later improvements led to development of the Zuni (5-inch folding-fin general-purpose aircraft rocket). The Zuni, equipped with a variety of warheads for air-to-ground use, became operational in 1957. Both the Zuni and the Mighty Mouse are still in our nation's arsenal.

Figure 2—Sidewinder, the nation's first passive infrared-homing air-to-air guided missile, on F-9F aircraft. This photograph was taken in 1956, the year Sidewinder was released to the Fleet.

Perhaps the most dramatic proof of NOTS' capability occurred during the Korean conflict when there was a pressing need for a tank-penetrating rocket. NOTS engineers used off-the-shelf components and imaginative determination to deliver the first batch of the ATAR (antitank aircraft rocket) for combat use only 28 days after the start of its development.

With the end of the nation's involvement in Korea, NOTS continued to develop products for Fleet use. It was recognized by this time that an expanding weapons technology was as crucial in peacetime as in wartime.

Associated Projects

When CalTech got out of the weapons development business at the end of World War II, more than just the rocket program at China Lake was at stake. CalTech also had a strong program in underwater ordnance at Pasadena. The Navy decided to keep its inherited CalTech programs under the single organization of NOTS, making facilities at Pasadena, Eaton Canyon, and Morris Dam responsible to the new NOTS Pasadena Annex and the Pasadena Annex responsible to China Lake. Underwater research and development facilities later included those at Long Beach and San Clemente Island, as well.

The Pasadena Annex operated as a part of NOTS until 1967, when a general reorganization of Navy laboratories resulted in the separation of the two organizations and the creation of the Naval Undersea Research and Development Center from Pasadena and its subsidiary facilities. In the intervening years, research in water-entry ballistics, underwater propulsion, torpedo components, total weapon system design, and related research in oceanography led to progressive weapon improvement and significant contributions to antisubmarine warfare.

Another post-World War II program to make use of NOTS facilities for a time was Operation Camel, a function of the Manhattan Project to manufacture high-explosive components for early nuclear implosion bombs. The Salt Wells Pilot Plant, still in use for a variety of NWC projects, was constructed to manufacture precisely machined nonnuclear explosive components used in early nuclear bombs. Another example of NOTS work during this period was BOAR (Bureau of Ordnance aircraft rocket), designed for a nuclear warhead.

Name Change

The China Lake facility never operated exclusively as a test station, yet its name, Naval Ordnance Test Station, seemed to indicate that this was its primary function. In 1967 NOTS received a more accurate name when a major reorganization of Navy laboratories resulted in the consolidation of facilities of similar function into "centers of excellence." At that time NOTS China Lake separated from NOTS Pasadena (now part of the Naval Undersea Center, featured in the July 1973 issue of *Naval Research Reviews*) and was combined with the Naval Ordnance Laboratory, Corona, to become the Naval Weapons Center. This reorganization came as part of a continuing review of the functions of Navy laboratories by the Naval Material Command in order to achieve a more effective use of each laboratory's unique resources.

With perhaps a longer record of continuous effort in guided missile development than any other organization in the world, the Corona organization had evolved from a National Bureau of Standards missile development division and several related groups. The Corona Laboratories were responsible for many innovative Navy programs including development of missile telemetry systems, pioneering studies in electro-optical and antiradar missile guidance, construction of the first analog computer installation capable of

accurately simulating the performance of a missile system under various flight conditions, basic research in infrared spectroscopy, and technical direction since 1954 of the entire Navy guided missile fuze research and development program. By 1971 almost all the facilities at Corona were closed, and most of its personnel absorbed by NWC at China Lake. As part of NWC, talents and developments that had their start at Corona continue to extend the Navy's record of creative achievement in weapon development and guided missile technology.

With its new name, NWC continued to operate in the NOTS tradition. In the 1960s increasing involvement of the United States in Southeast Asia played a growing part in determining priorities for the Center's work. Our defense leaders had no doubt that this work was vital: during the height of the Southeast Asia struggle, the Secretary of Defense credited NWC with being the source of over 75% of the air-to-air and air-to-ground weapons in use in that conflict.

NWC Products

Recent products of the Center support its mission as the principal Navy RDT&E center for air warfare and missile weapon systems. While NWC develops weapons that are valuable not only to the Fleet but also to the Army and the Air Force, facilities and capabilities are still kept flexible to maintain a wide range of technological avenues for immediate responsiveness to future defense needs.

Continuing improvements to the Sidewinder missile include the AIM-9H and the AIM-9L versions for improved tracking and maneuverability. Another major NWC accomplishment, Shrike, is the nation's first antiradar guided missile. First released to the Fleet in 1965, Shrike continues to be improved in new versions covering a broad spectrum of target radiation. Standard ARM (antiradiation missile), a legacy to NWC from the Corona Laboratories, has been another bright idea that has improved over the years. The high-speed version, HARM, offers broad-band frequency coverage, a large launch envelope, and a shorter time to target.

First issued to the Fleet in 1967, the television-guided Walleye I glide bomb has been proven in combat. Walleye II, the current version, demonstrates the effectiveness of its remote control and retargeting capability after launch. Condor, another offspring of the video age, was originally developed as a propelled TV-guided stand-off weapon against land targets and has since been adapted for use as a ship attack missile.

539-665 O - 74 - 2

Two other major NWC missile programs are Bulldog, an air-launched close-support missile using semiactive laser guidance supported by airborne or ground target designators; and Agile, a missile system emphasizing maneuverability, with an increased capability to acquire and intercept maneuvering air targets. Point defense saturation attack problems are being studied in connection with possible application of the Agile missile technology. The Chaparral and Sparrow missiles are being considered for vertical-launch point defense and are undergoing modification to permit firing from shipboard vertical launchers.

Free-fall weapon technology at NWC concentrates on improving weapon stabilization, safety, effectiveness, and reliability, and on designing weapons specifically fitted for use in high-speed aircraft. Categories of NWC free-fall weapons include retarded weapons, using retarding fins as an aircraft safety factor for close-in bombing; cluster weapons, containing fragmenting bomblets; and special-purpose weapons such as the Briteye flares for night-attack or search and rescue operations.

NWC employees are also currently working on a guided night attack weapon, an aircraft survivability program to reduce the vulnerability of naval aircraft to munitions, a study of thrust vector control to stabilize pilot ejection seats, the night observation/gunship program using an infrared sensor for night target acquisition, feasibility tests on a system to locate radiation targets in high-density electromagnetic environments, and many other programs concentrating on important aspects of defense problems.

Facilities

NWC today is one of the world's most complete RDT&E centers. Covering approximately 1,700 square miles, an area almost as large as the state of Delaware, the Center's physical complex includes Michelson Laboratory R&D facilities; extensive ground, track, and aircraft test ranges; a Naval Air Facility; and the Navy-owned community of China Lake. These facilities are equipped to handle every phase of the Center's work from basic scientific research and feasibility studies to design, development engineering, prototype production, and testing and evaluation of weapon components and systems.

Michelson Laboratory is the focal point of the Center's research and development effort. Named in honor of Dr. A. A. Michelson, distinguished physicist and Nobel Prize laureate, the laboratory provides approximately 11 acres of floor area for its laboratories and

engineering spaces, its computer facilities, and its machine shops. It is equipped for basic and applied research in chemistry, physics, mathematics, aerophysics, electronics, metallurgy, and ballistics, and for development work on propulsion, fire control, and guidance systems for rockets and other missiles. The laboratory is the heart of a complex of varied laboratories serving the approximately 5,000 persons, both military and civilian, who labor at many aspects of NWC's mission.

The Solid-State Research and Development Facility, one of the Center's many specialized laboratory buildings, is equipped for research and development in lasers, radar, electromagnetic interference, detector chemistry, microelectronics, and fuzes.

The China Lake Propulsion Laboratories, built as a pilot plant so early in the Center's history, are now functioning as a complex of special facilities for research, development, testing, and experimental production of solid and liquid propulsion systems, pyrotechnics, explosives, and warheads. The propulsion laboratory area covers about 50 square miles and includes buildings and test bays specifically designed for safely mixing, casting, extruding, curing, machining, and testing high-energy propellants and explosives.

Some of the other specialized facilities within NWC boundaries are a laboratory for warhead research and development, a radio frequency measurement facility, a missile components test facility, and a technical library.

More than 1,000 square miles of the Center's area are maintained as modern ground ranges and test tracks. A sophisticated and highly instrumented complex, these ranges may be thought of as outdoor laboratories, used in coordination with NWC's other facilities to develop effective weapon systems (Figure 3). Range facilities include the 37-mile-long G-1 and G-2 ranges used for testing rockets and guided missiles at launch and in free flight, a terminal ballistics range, and a crosswind range. The longest of the Center's three tracks is the 4.1-mile-long SNORT (supersonic naval ordnance research track). It is constructed to permit sustained runs of the heaviest carriages at speeds approaching 6,000 feet per second.

The Center's aircraft ranges cover an area of 360 square miles. They are used for testing the performance of bombs, free-fall weapons, and other ordnance items under actual air-launch and flight conditions (Figure 4). These aircraft ranges are used for testing weapon release computers and fire control systems, calibrating aircraft radar and angle of attack, developing tactics for aircraft delivery of special weapons, conducting operational evaluation of weapons, training Fleet pilots, and testing ordnance. The Randsburg

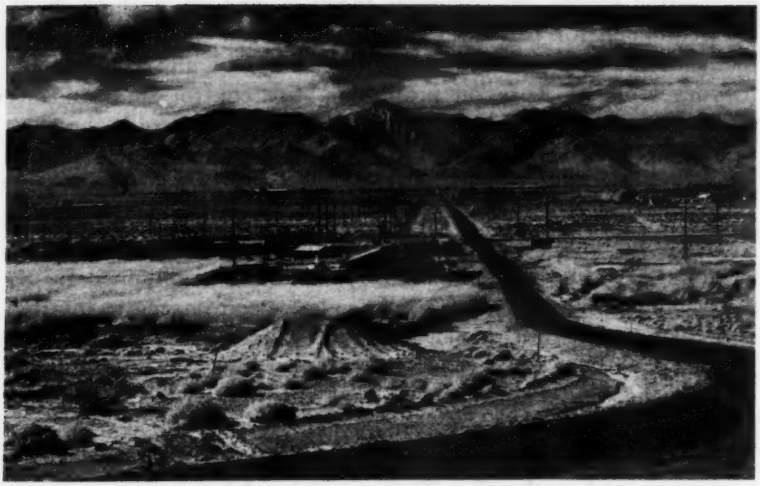


Figure 3—A few of the many specialized buildings serving the range areas, NWC's "outdoor" laboratories." The Sierra Nevada looms in the background.

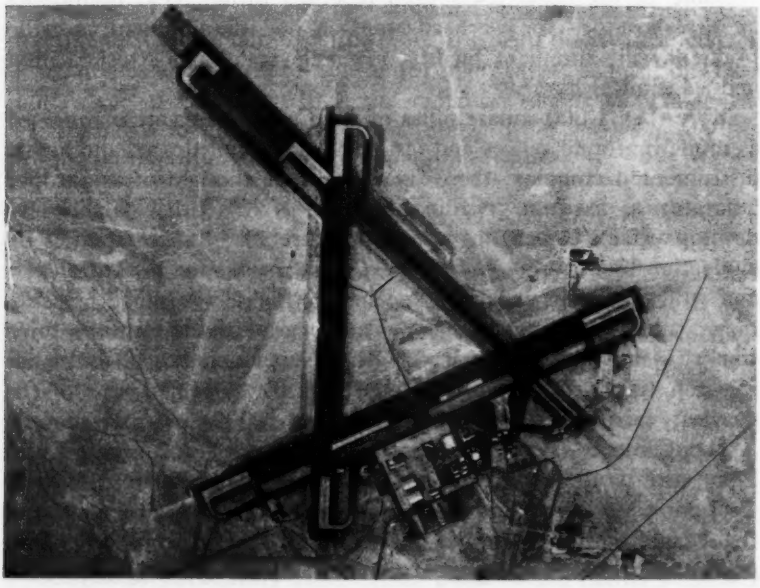


Figure 4—The Naval Air Facility. A separate command under the military control of the NWC Commander, this activity offers valuable support to the technical work of the Center.

Wash test area, located 25 miles from the China Lake complex, is used for testing of fuzes and for electronic warfare tactical environmental simulation.

Research Today

Today NWC operates as one close-knit organization, where ideas from basic research are carried on through development and evaluation to a finished product. Applying the lessons of the past, the Center encourages freedom in work. This is not a manufacturing plant turning out a specific product, but a research and development activity where the success of projects is dependent on the creativity of individuals and where maximum flexibility assures responsiveness to Fleet needs. The Center's broad program encompasses basic and applied research in the physical sciences and engineering, development engineering, and testing and evaluation of weapon systems and components, as well as a growing involvement in applications of defense technology to domestic areas.

Independent research and independent exploratory development at the Center are sponsored through laboratory discretionary funds, about 4% of NWC's fiscal year 1973 budget of $180 million. A three-fold purpose motivates distribution of independent research funds: (1) to use the fruits of basic research for practical applications, (2) to sponsor research for which the development departments need results, and (3) to support continuing work important for its fundamental scientific contribution. Independent exploratory development money is typically used to finance the small, time-limited project in need of short-term funding. It allows the scientist the chance to pursue a bright idea quickly, to demonstrate its promise so that he can get funding through regular channels. Research discoveries are vigorously applied in exploratory development, where research scientists work closely with the Center's development departments.

The Center today emphasizes research that is fundamental but also relevant. NWC management realizes that a career based solely on problem solving would offer insufficient challenge to the high-caliber research scientist and that a viable research program requires freedom to risk detours down blind alleys. The scientist, in turn, finds day-to-day contact with practical problems to be a "reality check" on the research he conducts in his fundamental area of interest. He can also derive gratification from immediate results in his function as a consultant to NWC development departments, other government laboratories, universities, and industry.

Ongoing research projects at NWC are many and varied. Research in physics includes continuing investigations into the physics of the solid state, with emphasis on the optical properties of solids as related to their structural and electrical properties. Metal physics research studies the properties of point defect clusters in metals, with the ultimate goal of designing superior metals (Figure 5). Another continuing research project studies the physics of optical

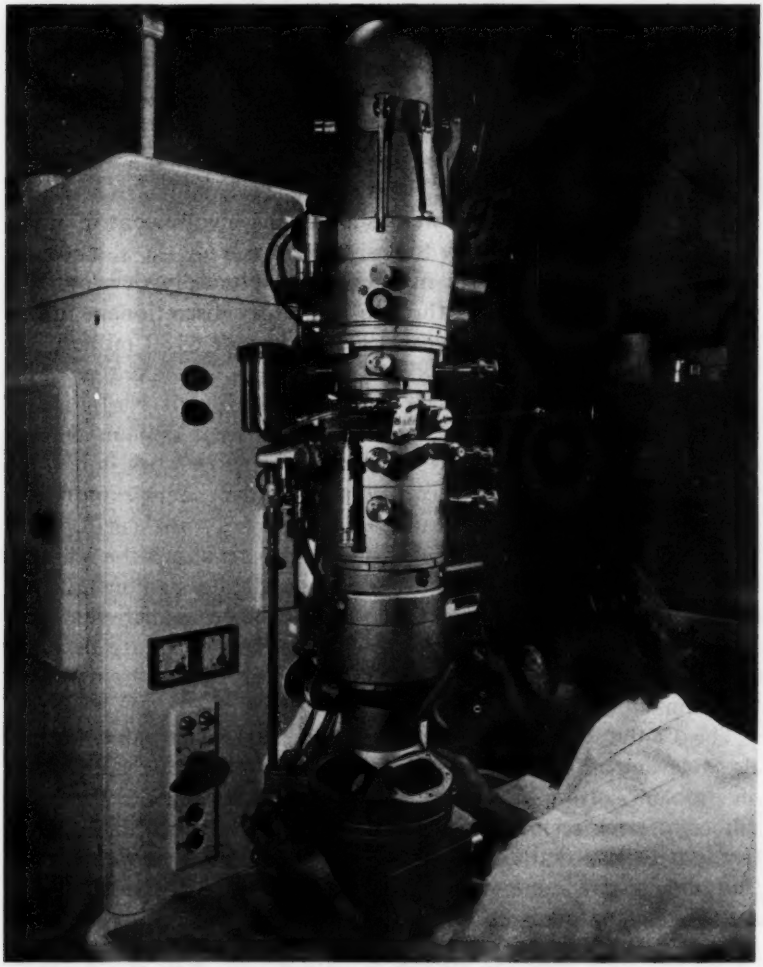


Figure 5—Transmission electron microscope used for a study of the internal structure of metals

surfaces in order to improve laser optical components. Research continues, too, on the theoretical study of the influence of photocarriers on surface charge profile and surface barrier electroreflectance. The technological potential of amorphous or glassy semiconductors is being explored. Modulation spectroscopy is being used in several areas of applied research (Figure 6).

Other studies are revealing important information on such diverse subjects as lasers, detonation turbulence, microwave acoustics, two-photon absorption and emission phenomena, structural properties of epitaxial films, and marine hydrocarbonoclastic bacteria.

NWC chemists pursue basic and applied research in organic and inorganic chemistry. They are studying the chemistry of alkylhydrazines, many types of polynitrogen compounds, transition metal complexes, and many other compounds and mixtures. Nuclear magnetic resonance, electron spin resonance, and X-ray crystallography are being applied to a variety of structural studies. Another research project studies chemiluminescence, a phenomenon with many applications.

Research leading to the development of improved propellants, explosives, and pyrotechnics seeks to gain a fundamental understanding of thermal decomposition of explosives and of the mechanisms of composite solid propellant combustion. This research includes studies in ignition, combustion instability, decomposition and deflagration of solid propellant ingredients, combustion mechanisms of composite solid propellants, air-augmentation rocket combustion, and metal combustion.

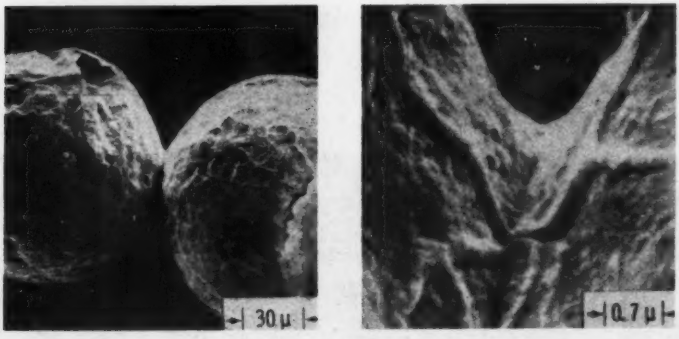
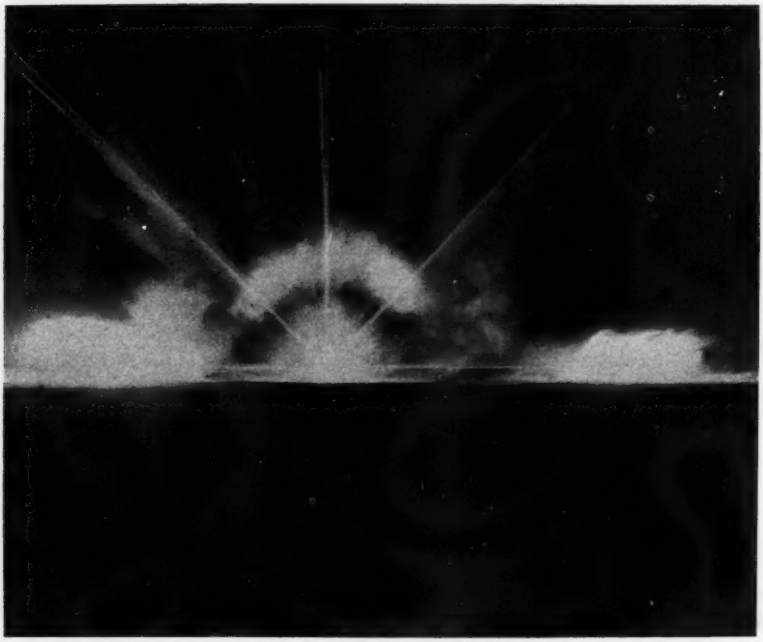


Figure 6—Two aluminum particles joined by bridging (left) and close-up of bridge area (right). This photomicrograph is one of many obtained by a scanning electron microscope during studies of the combustion of composite solid propellants.

Research in mathematics is pursued in the areas of statistics and probability, applied mathematics, numerical analysis and programming, and algebra and combinatorial theory. Work is being done on optimal control theory and pattern recognition. The development of a methodology for determining optimal search/scan techniques for weapon control and missile sensor systems is being investigated.

Other research includes numerous investigations in meteorological processes, including earthquake analysis and weather modification studies. The Technology Transfer Program is finding ways to apply NWC's defense technology to such nonmilitary domestic areas as biomedicine, pollution, and transportation.

This introductory article gives only a fleeting glimpse of NWC and of its RDT&E programs. The following three articles present snapshot views of representative ongoing research projects.



A warhead explosion

Dividends of Dye Laser Research

Richard S. Hughes
Physics Division

The first Navy laboratory to enter the dye laser research field, NWC initiated an independent research program to investigate the potential of the tunable dye laser in 1969. This program has put fluorescence, a phenomenon of nature, to work in a new way.

When organic dyes are dissolved in an appropriate solvent and excited by an appropriate energy source, they exhibit a most useful property—fluorescence in a broad band by the dye molecules. Fluorescence, where excited molecules rapidly emit light of longer wavelength than the light they absorb, is actually the phenomenon that sets off laser action. When fluorescing material (gas, liquid, or solid) is put in the right kind of optical cavity, stimulated emission will cause a tremendous buildup of light. The directional selectivity of the laser cavity causes the stimulated emission to occur in a collimated, very intense beam of light. So fluorescence, a random isotropic phenomenon, initiates laser action, a very nonrandom, very directional phenomenon.

It was not apparent what the payoff of our tunable dye laser program might be for the Navy, but we anticipated a number of defense applications. An unexpected dividend of our program promises to save lives and greatly increase effectiveness of night search and rescue (SAR) operations. Although not making use of a dye laser, this new SAR system was conceived as a direct result of our dye laser research program.

Laser Search and Rescue System

In the course of NWC's dye laser research, we noted that one of the dyes that lases exceedingly well is fluorescein sodium salt (FSS), the widely used sea dye marker. This observation led to our promising night SAR system.

Every Navy life vest and life raft contains packets or canisters of sea dye marker, which fluoresces yellow-green under the stimulus of sunlight. Sea dye marker is presently useless for night SAR, where existing search methods are slow and relatively ineffective. Rescue helicopters presently fly over the search area at approximately 90 feet in elevation at speeds of about 50 knots, scanning the area with three

539-665 O - 74 - 3

searchlights. This archaic search technique offers the searchers a low search rate, a low probability of detection, and a high false alarm rate.

The laser SAR system that we have developed will allow the rescue craft to fly at 500 feet in elevation at speeds up to its maximum. With this new SAR system, night search operations over water can cover approximately 30 mi^2 per hour with a 99.8% probability of detection and a false alarm rate of less than one per three hours of operation. This completely automatic night SAR system has been developed for HC-7, the combat SAR squadron at the Naval Air Station, Imperial Beach, Calif.

The primary components of the system are a nitrogen laser which excites the sea dye marker, an optically and electronically filtered detector and a three-sided spinning mirror scanner that synchronously scans the laser beam and the field of view of the detector back and forth across the ocean. The entire system is contained in a pod that is mounted on the side of the helicopter (Figure 1).

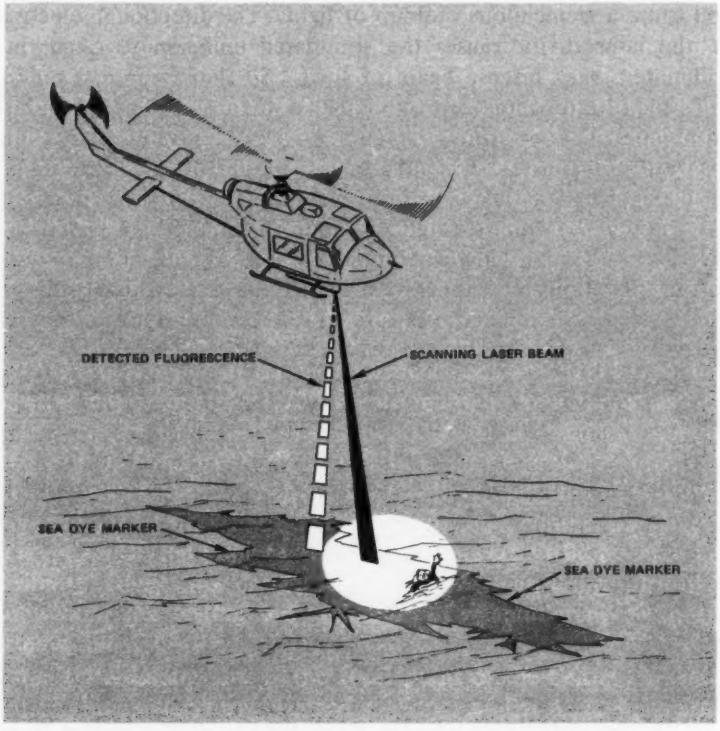


Figure 1—Laser system for night search and rescue at sea

When the laser beam hits an area of water containing sea dye marker, the dye becomes excited and fluoresces. Upon detection of the fluorescence, the system emits an audible tone alerting the crew chief that the dye has been spotted. A visual indicator shows whether the dye is to the right, to the left, or directly below the flight path of the helicopter.

During the pickup part of an SAR mission, the helicopter must hover approximately 40 feet above the water. Because of the lack of good visual references at night, hovering at 40 feet is both difficult and dangerous. The system developed at NWC also has a hover mode which provides an effective visual reference, thus making the pickup both more easy and more safe.

Our effective new SAR system will be delivered for Fleet evaluation in mid-1974. The Federal Aviation Agency has also indicated interest, and if the system performs as well under actual SAR conditions as it did under test, we expect it to be adopted widely for night SAR missions.

The facilitation of effective night SAR operations at sea is only the first of several potential applications that we expect to pursue as outgrowths of our basic dye laser research project. For example, we plan to investigate impregnating lightweight, compact, foldable plastic panels with dyes for an inland night SAR capability (Figure 2).

Tuning Techniques Investigated

In the principal thrust of our research in the Physics Division of NWC's Research Department, we are most interested in investigating the potential of the tunable dye laser. It is the band nature of the dye molecule's fluorescence during laser action that most intrigues us. This band property offers a means of tuning a laser; that is, continuously changing its output wavelength over a broad spectral range.

In the course of developing the tunable laser, we have been investigating unique physical and geometrical optics techniques coupled with organic dye laser technology. To produce pulsed dye laser action, we have used one of the following: a flash lamp, a pulsed nitrogen laser, or a cavity-dumped (frequencies up to 10 megahertz) argon-ion laser to excite the dye. For continuous wave (cw) dye laser action, a cw argon-ion laser is used. The organic dye solution is contained in a specially constructed flowing dye cell. Provision is made to circulate the dye solution so that any thermal problems encountered at the higher pulse repetition rates or in the cw mode are eliminated.

We have investigated three different tuning methods, each more rapid than the one before it.

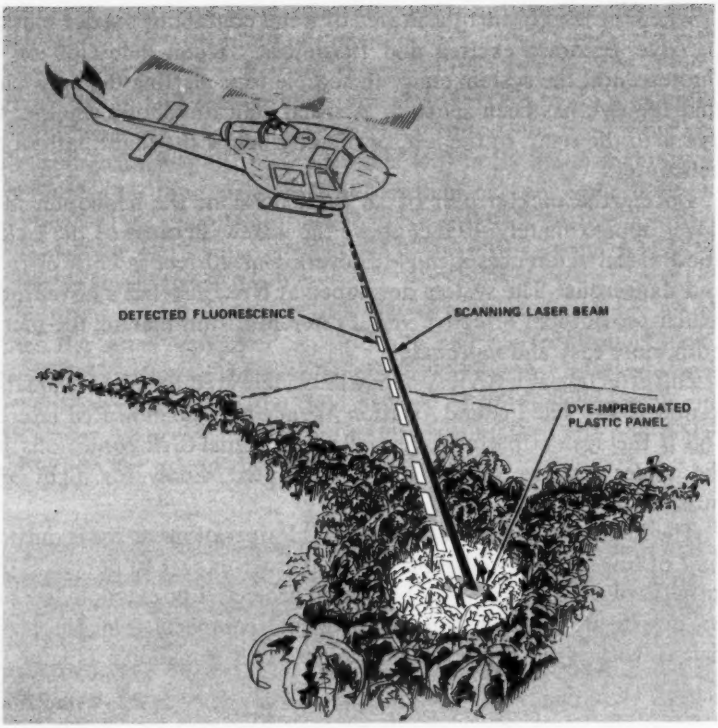


Figure 2–Proposed laser system for night search and rescue on land

In the first phase of our program we investigated an electromechanical (EM) technique, a type of tuning accomplished by the motion of a laser cavity component resulting from an applied voltage. We investigated three different types of moving components: a 3-kilohertz resonant frequency galvanometer-driven mirror, a 3-kilohertz resonant frequency piezoelectrically scanned Fabry Perot interferometer, and a commercially available bimorph strip laser beam scanner, All three systems provided for rapid tunability, but we found that the hysteresis and creep characteristic of piezoelectric crystals and bimorph strips made the tuning of these two systems unreproducible. We concluded that the galvonometer-tuned laser was the best of the EM-tuned dye lasers evaluated; its maximum tuning rate was 10^5 nm/sec.

Results of our EM investigations were encouraging, but we felt we could achieve much higher tuning rates using techniques that would not rely on moving parts. The maximum tuning rates available using

EM techniques are limited by the resonant frequency of the moving component. So we began to investigate acousto-optical (AO) tuning (Figure 3), accomplished by the interaction of an acoustic wave with the intracavity laser beam. This technique has no moving parts, but depends for its tuning on sound waves generated in a crystal. Since the upper limit of the AO tuning rate is determined only by the time it takes for the acoustic wave to cross the optical wave, we have achieved a tuning rate with this technique that is 1,000 times faster than that achieved with an EM techniques.

Our transverse AO-tuned dye laser makes use of a Bragg diffraction cell placed in the laser's optical cavity. A traveling acoustic wave within the Bragg cell deflects the light. A change in acoustic frequency produces a change in the deflection angle, changing the angle of incidence upon the diffraction grating. The diffraction grating acts as a wavelength selective mirror; the wavelength reflected (and hence also laser action) depends upon the angle of incidence. Thus, the dye laser's output wavelength (color) is swept by sweeping the acoustic frequency. In addition to a greater reproducibility and tuning rate than those provided by any of the EM tuning techniques, greater reliability and longer life can be expected from a technique without moving components.

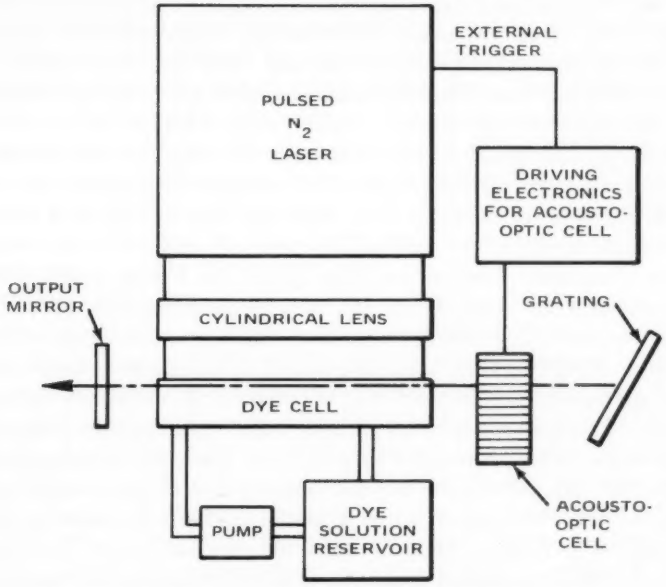


Figure 3– Transverse acousto-optic tuned organic dye laser

The third dye laser tuning technique investigated at NWC takes advantage of one of nature's fastest effects, the electro-optic (EO) effect. The EO tuning technique makes use of an EO filter or deflector placed within the laser's optical cavity. EO tuning rates are limited by the time required to apply or remove a voltage to the EO element. Tuning rates, on the order of 10^9 nm/sec, are 10 to 100 times faster than those achieved with the AO technique.

Dr. John L. Hall and associates at the National Bureau of Standards at Boulder, Colo., have applied an EO technique to the tuning of lasers, but their research has been geared toward producing a very fine spectral line and tuning slowly. NWC is the first laboratory to use the EO technique for ultrarapid tuning of lasers.

New Computer Concept

Recently we have been addressing ourselves to the following research question. How can the organic dye laser help computer technology? A new kind of optical memory system, using this laser, holds promise for the computer of tomorrow. Today's computers perform an almost miraculous array of functions, an array, however, that can still be broadened.

In late 1972 at an ONR-sponsored computer symposium, Dr. Paul Moose of the Naval Undersea Center at San Diego called for a computer breakthrough. He stated that the Navy has many potential computer applications requiring smaller, more rapid computer systems than have yet been developed. For instance, a submarine or a small surface craft simply cannot accommodate the computer system today necessary to perform the 30,000,000 complex multiplications per second required to analyze data from the transducers of a towed hydrophone array.

Like many other laboratories throughout the United States, NWC works toward achievement of the sort of breakthrough called for above. A joint ONR/NWC program works on a facet of an optical computer—a high-density fast-access digital memory system that makes use of specialized crystal defects ("M" centers) in potassium chloride crystals. Random-access beam steering will be accomplished through use of dispersive elements and a tunable dye laser. Or, simply stated, we at NWC are helping to develop a computer memory addressing system where information can be recorded or retrieved through rapid scanning of a focused spot of light on the surface of a crystal.

In this ONR-sponsored program, several laboratories are working on facets of this promising computer research project. The Naval

Research Laboratory in Washington, D.C., is producing and studying the highly specialized crystals that will be the memory element of the new computer. The Coordinated Sciences Laboratory at the University of Illinois is putting the various computer elements together into a system and investigating the entire system parameters. And here at NWC we are working on the development of the rapid-scan laser needed for this new computer concept to be effective.

Optical Memory Application

In our computer addressing research, polarized light is required to record information within a photodichroic crystal. The laser beam is ideal for this function—it produces polarized light that is intense and directional, and that can be readily manipulated. The objective of the optical memory program is to produce an extremely dense computer storage element that would store one million bits on a crystal of only a square centimeter in size. Also, a random access time, that is, the time required to scan from one point within the crystal to any other point, is to be less than one microsecond.

It is a great challenge to develop a laser that can scan rapidly enough to accomplish these objectives. James L. Jernigan of the Physics Division has been working on this project for about a year and has uncovered some interesting physical phenomena that have not been previously observed. The use of two unusual argon-ion lasers has enabled him to make very precise observations. Our cavity-dumped argon-ion laser enables us to extract from the laser cavity at very high repetition rates, up to 10 megahertz, pulses of practically any width that we choose, permitting close examination of the dye laser's pulse response. Our 20-watt cw argon-ion laser provides for not only high power operation but also the simultaneous operation of two or more dye lasers.

Figure 4 diagrams functionally the apparatus for deflecting a laser beam for accurate positioning on discrete geometrical positions on a two-dimensional substrate of the photodichroic memory. The EO tunable dye laser performs as the read/write energy source in tandem with a dispersive system that passively performs the necessary beam steering before the light impinges onto the optical memory. The dye laser is tuned to discrete wavelengths that are steered by means of the dispersive system—a prism, grating, and lenses as required to generate a small spot on the substrate. The dispersive system changes the direction of the optical wavefront as a function of wavelength; therefore, positioning of the beam on the memory substrate becomes a

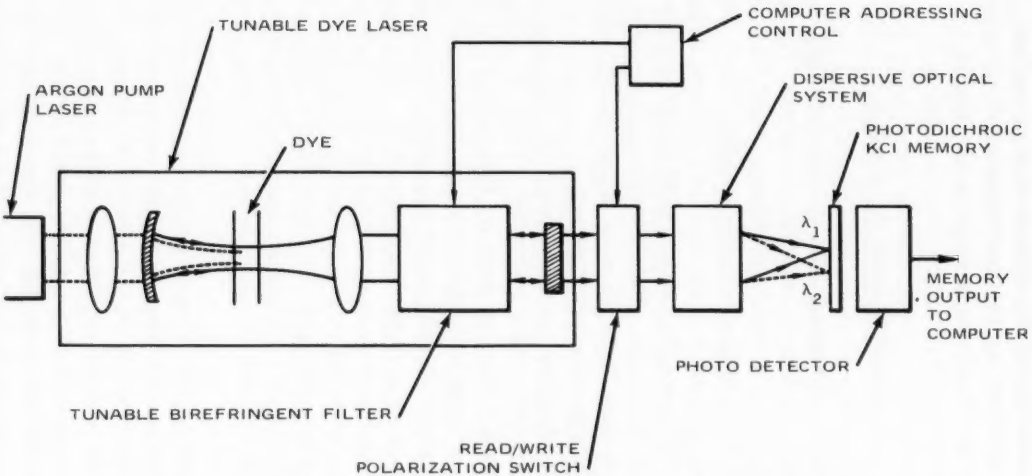


Figure 4–Functional diagram of a tunable dye laser optical memory addressing technique

function of the laser's wavelength. A read/write polarization switch changes to the different polarizations required for reading and writing.

Exploration of several tuning techniques eventually led to the configuration shown in Figure 5. This system consists of two resonant cavities coupled by a beam splitter. Each cavity contains a polarizer and a birefringent crystal Lyot filter folded through the end mirror. Each cavity contains two sets of orthogonal polarized axial modes; the frequencies of each set of these modes are uniquely and independently determined by the optical path length through each birefringent crystal. By using two cavities, rather than one, we obtain additional filtering. The cavity lengths must be carefully chosen so that each cavity resonates at a frequency mode that is common to both.

We plan also to construct a basic dispersive optical system similar to that shown in Figure 6. The high dispersion grating diffracts the light through a telescope of suitable power to produce the required number of bits per centimeter in the plane where photodetectors are located. We will investigate use of the cross-dispersion technique, where a prism is introduced into the beam before the grating to prevent overlap of the higher diffraction orders by separating them into the vertical dimension. Data storage will thus be possible in two dimensions. We will also study holographic gratings, which offer considerable promise of simplifying this portion of the addressing system. Noise and dispersion effects will have to be dealt with, however, before holographic gratings can be implemented in the system.

Many Dyes Suitable

While progress is made on the laser components of the proposed optical memory system, NWC scientists continue to seek ways to improve all facets of the tunable dye laser, including the dyes themselves. Dr. Peter R. Hammond of the NWC Chemistry Division is developing a number of fluorescent dyes for the Naval Electronics Laboratory Center in San Diego. The thrust of his research is twofold: toward stability and toward efficiency. The ideal dye for laser use is very stable, so that as the dye molecule is excited, it does not disintegrate, but lasts a very long time. This dye is also very efficient, that is, a large percentage of the light used to excite the dye is emitted by the dye at a different wavelength. Although the NWC tunable laser program is using products from this dye research, the real impetus of the research is toward development of blue-green dyes for NELC's underwater applications.

Dr. Hammond's research involves the detailed study of a phenomenon called "exciplexes," or changes in equilibrium between the

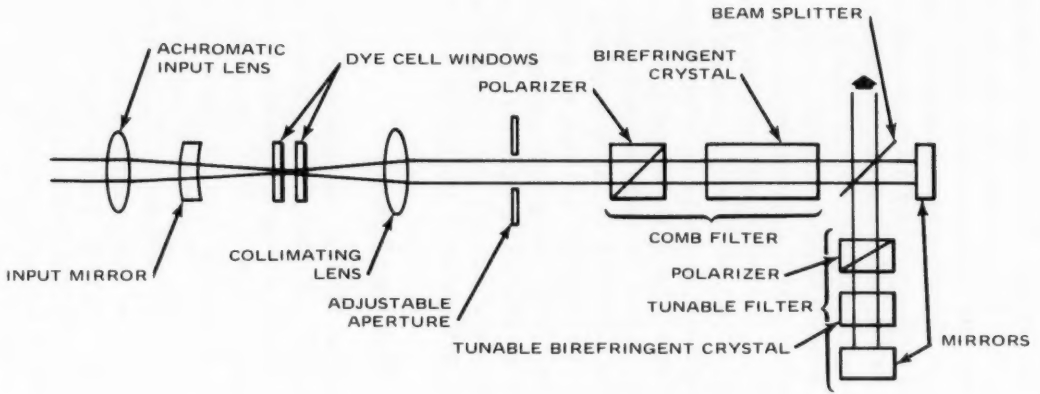


Figure 5—The modified Fox interferometer tuning technique

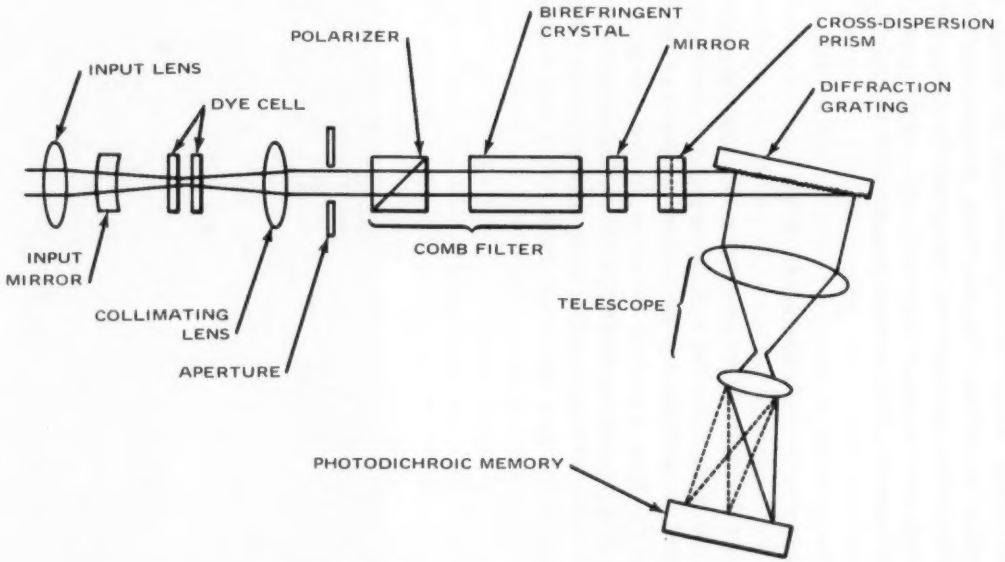
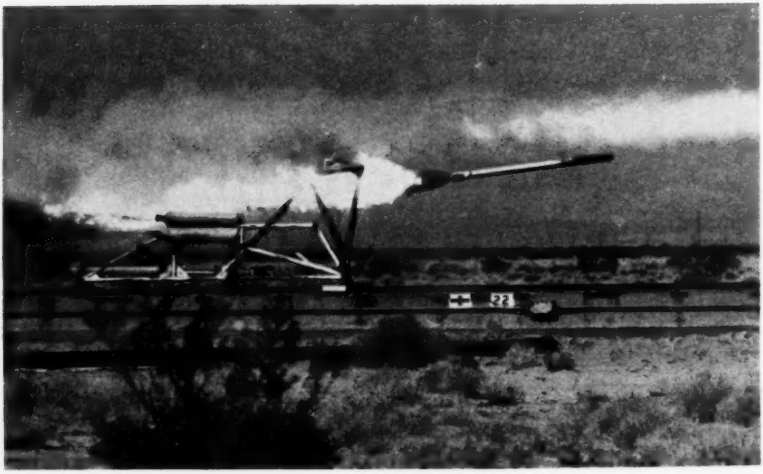


Figure 6—Experimental setup for a basic dispersive optical memory system

ground and excited states of molecules. These exciplexes—both the proton exciplex and the molecular exciplex—relate respectively to changes in acidity and basicity, and to the electron-acceptor/electron-donor properties of the dye molecule. Exciplexes directly affect the fluorescent and absorption characteristics, which in turn determine the required degree of laser pumping power and the breadth of tuning range. Organic dyes of the coumarin family have been the most promising performers to date under this program. In particular, a broad tuning range, covering nearly half of the visible light spectrum (from 447 to 569 nanometers), has been achieved with 7-hydroxycoumarin dyes.

Future Applications

We expect the utility of the dye laser to be greatly increased by the experimental work on tuning techniques and dye synthesis presently being carried on at NWC. As we achieve increased tuning rates, we expect the dye laser, a tool for tomorrow, to find new uses, as promising and as impossible to predict as the optical memory addressing technique. And, with the success of our SAR system in mind, we are keeping our eyes open for other dividends of dye laser research.



A rocket over the testing range

Improvement of Mirror Surfaces

Jean M. Bennett
Physics Division

Many of the Navy's most significant military problems are solved today with the help of a narrow, intense beam of light—the laser. The performance of high-energy laser systems, and also the performance of many of the Navy's operational weapons such as the Sidewinder, Walleye, and Agile missiles, the FLIR (forward looking infrared) system, laser guided bombs, and devices with optical fuses, depend on the quality of the mirrors used. In the Physics Division of NWC's Research Department, studies of the optical properties of solids related to their structural and electrical properties are being conducted that have produced fundamental information which will result in notably improved optical components in the Navy's existing guidance and detection systems, and in future systems already on the drawing boards.

The mirrors that will be used in the new high-energy laser systems have extremely stringent requirements. Each mirror must reflect a maximum amount of the light energy that strikes it. In addition, in order not to degrade the quality of the system, the mirror must reflect the light specularly—that is, in true mirror fashion—rather than scatter it in all directions. And the mirror must not be made of a material that will burn up when it reflects large amounts of energy.

A mirror's reflectivity varies as the wavelength, or color, of the light varies. For example, the reflectivity of a mirror may be 95% for green light but only 50% for violet light. The light that is not reflected is absorbed in the reflecting material. Reflectivity also varies from one material to another. The best reflecting materials for visible and infrared light are gold, silver, and aluminum.

Whether light is absorbed or reflected specularly from a mirror depends primarily on the roughness of the surface. In a sense, even the finest of mirrors can be termed rough—man has yet to make an atomically smooth mirror. This roughness may refer to surface irregularities that are many times smaller than the wavelength of the light they are designed to reflect. It is this "microroughness" that we are studying with the help of instruments devised by members of the Physics Division.

Our specialized instruments measure optical properties of materials *in situ*, surface roughness, and scattering from extremely smooth mirror surfaces. With our new instruments we measure extremely small amounts of light scattered by mirrors, both in the infrared

and the visible and ultraviolet regions of the spectrum. We also study the properties of mirror coatings and measure the small changes that occur when the coatings are subjected to different kinds of contamination. And we observe the actual mirror surfaces, using a TV scanning system, with which we can measure minute differences in height on the surfaces. These differences, only a very small fraction of a wavelength in size, are much smaller than can be observed with an electron microscope.

Optical Evaluation Facility

One of our precise instruments, the optical evaluation facility (Figure 1), was designed by Harold Bennett of the Physics Division and built, assembled, and tested in NWC's Michelson Laboratory. The instrument uses a large hemispherical mirror, called a Coblentz sphere,

Figure 1–Phil Archibald aligns the sample in the laser beam on the optical evaluation facility

to collect all the light scattered from a sample mirror. Samples can be either plane or concave and up to 16 inches in diameter.

The optical evaluation facility measures light scattered very close to the specular direction, a capability not found in other instruments of this type. Measurements can be made of the magnitude and angular dependence of forward scattering from the test mirror within 2 degree of the specular direction. Since lasers are used as light sources, very small amounts of scattered light can be measured with this sensitive instrument, which also measures extremely high reflectances very accurately. Both scattering and reflectance measurements can be made at a whole series of laser wavelengths ranging from 0.35 micron in the ultraviolet to 10.6 microns in the infrared.

Polarization-Modulated Ellipsometer

Another of our unique optical instruments is the polarization-modulated ellipsometer (Figure 2). The original version of this

Figure 2–Harold Bennett (right) and Dennis Burge examine the polarization-modulated ellipsometer, mounted on an ultrahigh vacuum system

instrument was developed by Steven Jasperson, a consultant to NWC who teaches at Worcester Polytechnic Institute in Massachusetts. The ellipsometer has been modified and improved by Dennis Burge and Robert O'Handley of the Physics Division, in consultation with Jasperson.

The polarization-modulated ellipsometer automatically analyzes the state of polarization of a beam of light reflected from a sample. When this is compared with the known state of polarization of the light before reflection, the effect of the sample can be deduced, giving valuable information about the optical properties of the reflecting material.

The ellipsometer is mounted on an ultrahigh vacuum system so that measurements can be made on mirror coatings that are prepared and maintained in controlled atmospheres of various gases. The principal advantage of this new instrument is that once it is properly aligned, none of its parts have to be moved or adjusted (conventional ellipsometers require at least one manual adjustment per measurement). Thus the instrument is relatively fast, capable of processing and recording data at a rate of several sets per second.

Because of a unique design employing a quartz transducer, the changes necessary to make two independent measurements are built into the light itself by modulating its state of polarization. This is part of the reason why the high precision (capable of detecting 0.002 monolayer change in oxide film thickness) of this ellipsometer is an order to magnitude better than that of unmodulated conventional ellipsometers. Stability and accuracy of the instrument are comparable to that of conventional ellipsometers.

The polarization-modulated ellipsometer is used to study the effects of small concentrations of contaminants (such as oxygen, water vapor, hydrogen, and carbon dioxide) on the reflectance of a freshly prepared mirror surface such as silver. Our studies point to the harmful effects of oxygen and water vapor upon the reflectance when the highest reflectance is desired. Our conclusion is that controlling the partial pressure of water vapor and oxygen during deposition is important if silver films of the highest reflectance are to be obtained.

The ellipsometer has been in operation for about a year, and has been undergoing significant improvements during that period. Most recently, it has been modified to allow heating and cooling of the mirrors. This modification, extending the instrument's capability, enables us to make studies of annealing and quenching effects. Furthermore, we can now measure resistivity of the mirrors and study the temperature dependence of the optical properties of materials,

surface plasmon effects, and oxidation effects in amorphous semiconductors.

Interferometric Surface Scanner

A third instrument helpful to our work is an interferometric surface scanner (Figure 3), developed by Jean Bennett to characterize quantitatively microroughness on mirror surfaces. With this unique instrument, multiple beam interference fringes, which contour the irregularities on mirror surfaces, can be observed visually or recorded using a special slow-scan TV camera. Data from the TV camera are then fed into a minicomputer and automatically processed.

This automated system directly measures the root-mean-square roughness, height distribution function, mean slope, and other satistical properties of mirror surfaces. It is invaluable for detecting extremely small amounts of roughness, for example, the root-mean-square roughness of less than a five-hundredth of a wavelength of light (about 8 angstroms) of the best polished fused quartz mirror surfaces produced by the NWC-developed bowl-feed polishing process.

Figure 3–Jean Bennett adjusts the interferometer to obtain sharp interference fringes contouring the irregularities on a mirror surface

The interferometric surface scanner now provides a direct and nearly indisputable measure of the surface irregularities on optically polished surfaces.

Light Absorption Studies

These precise instruments have helped us to identify mechanisms that cause absorption of light by mirrors and thereby reduce their reflectivity. We have found that a small increase in surface roughness causes a dramatic increase in light absorption. Visible and ultraviolet light falling on an irregular surface can stimulate longitudinal waves of the conduction elections, or surface plasma waves; the magnitude of this effect increases significantly with increasing surface roughness. In the infrared region, the interaction of conduction electrons with the surface produces additional absorption known as the "anomalous skin effect." This effect, too, increases with increased roughness.

When surface plasma waves are excited, some of the light is absorbed, with a corresponding decrease in the percentage of reflected light. The surface plasma waves decay rapidly, giving up some of their absorbed energy, but the resulting light is emitted in random directions. This scattered light is undesirable in optical systems. Other energy from decaying waves becomes heat in the mirror material. The anomalous skin effect also can cause significant damage to a mirror surface in a high-energy laser system.

Ironically, the above absorption phenomena occur with greatest effect in the very metals that are the best reflectors. When we can eliminate or significantly reduce these effects, it will be possible to produce metal mirrors of the highest reflectance.

Irregularities Reduced

Having established the existence of effects reducing mirror reflectivity, we are working on ways to diminish these effects. Investigation of polishing techniques to reduce surface irregularities led to the development of new commercially usable techniques that produce significantly improved mirror blanks. The NWC-developed modified bowl-feed technique can now be used to produce polished quartz mirror blanks that are far smoother than any previously available commercially polished blanks. The root-mean-square roughness of the best polished fused quartz mirror surfaces produced by the bowl-feed polishing process is about 8 angstroms, whereas the root-mean-square roughness for typical commercially polished glass and metal mirrors

ranges from 20 to 80 angstroms, depending on the mirror material and polishing techniques used.

The polishing technique developed at NWC differs from commercial techniques in that the polishing compound is fed continuously over the polishing lap, against which the mirror blank is held. A standard commercial machine was modified to include a bowl in which the polishing compound is mixed with water. As the bowl and lap turn, a small adjustable paddle diverts the flow of the mixture over the lap. This technique was given the name bowl-feed to distinguish it from the common fresh-feed technique used commercially, in which a fresh solution of polishing compound is introduced intermittently onto the lap. The bowl-feed technique produces smoother surfaces because it allows increased control over the size of the polishing particles.

With the help of our unique instruments, the Physics Division is making a detailed study of the factors contributing to imperfections in vacuum-deposited mirror coatings, with confidence that careful, complete research in this area will result in further improvement in mirror quality.

Members of NWC's environmental team at work

Optimal and Classical Controls

G. A. Hewer
and
R. B. Leipnik

Mathematics Division
Naval Weapons Center

Physical systems–ships, planes, and missiles in particular–do not always operate as we might wish. This may be due to malfunctions, design problems, or control problems. Several groups at NWC, among them the Mathematics Division of the Research Department, have been studying control problems of present and future Navy systems. More definitely, we consider systems, subsystems, and individual components of the recent past, the present, and five, ten, fifteen, even twenty years into the future. This wide span is dictated by a dynamic and intricately balanced technology, combined with long service lives for successful designs and for some equipment specimens. Control specialists must also reckon with rapidly changing techniques in software–algorithms, languages, and programs–and improved system models and measurement methods, as well as new concepts in control theory proper. The changing tactical, strategic, and politico-economic realities cannot be forgotten, as recent events insistently remind us.

What then can we expect in twenty years? Ships and aircraft will be smaller and faster, missiles more diversified, and countermeasures more elaborate. Skimmers and semisubmersibles will supplement surface ships and submarines. Controls will, as always, be physically inconspicuous, and as costly as they are essential. Adaptive automatic controls will govern some routine ship procedures as well as guns, drone/missile launches, and aircraft/helicopter operations. The associated computers, intercommunicating but potentially autonomous, will be rugged and golf-ball-size, though as capable as today's fragile room-size machines.

Within the next ten years, we can expect to see some of these innovations. For example, highly maneuverable missiles, guided by lasers and controlled by softball-size on-board computers, will be launched from programmable drones. Already, controls of the elaborate moon-ship type are planned for the newer submarines. Predictive controls are currently projected for VTOL/STOL operations on mini-carriers under stressful sea conditions, and so forth.

All these control systems depend on understanding of the system to be controlled and on sufficiently frequent and precise monitoring of the outputs and inputs. However, these systems differ in important respects. Control people classify controls as open-loop, closed-loop, or feedback, and also as optimal or classical. We shall try to illuminate these helpful distinctions—both in words and in mathematics—in the course of explaining how a control is designed. Suppose we know some behavioral parameters and at least part of the tentative structure of a system. This system may be automatic or some man-machine combination. We also have information on the system inputs. Suppose also the output objective to be reached is given, along with a general way to measure its fulfillment. Then a mathematical calculation can prescribe an ideal corrective input signal, ideal parameter values, and structural characteristics which (on the average) bring the system performance as near as possible to the optimum. The ideal control signal therefore is called an *optimal control* signal. Likewise, we have optimal control parameters and optimal control structures, which we will not discuss in this paper.

Controls need not be optimal to be useful. In fact, most control signals in use are nonoptimal on the basis of any popular performance index. Why is this? The original expense of mechanical and electrical components, their maintainability, and the ease and quickness of design methods for classical (nonoptimal) controls are often preferable to those for optimal controls. As usual, the trade-offs between cost and performance must be kept in mind.

Classical Design

The design methods for classical controls were developed between 1925 and 1940. They are based on Fourier-Laplace (frequency domain) analysis. This analysis in turn depends on system models defined by linear differential or difference equations, preferably with constant coefficients.

Grant now the validity of a linear constant-coefficient model of the time-domain form

$$H(t)f(t) = A(t)g_0(t) + B(t)g_1(t) = g(t) \tag{1}$$

$$y(t) = C(t)f(t) + D(t)g_0(t) + E(t)g_1(t). \tag{2}$$

Here $H(t)$, $A(t)$, $B(t)$, $C(t)$, $D(t)$, $E(t)$ are system operators, usually differential or difference operators; g_0 is the raw input; and g_1 is

the control signal input. The quantity f is the state of the system, and y is the final output. The uncontrolled system results from setting $g_1 = 0$. The above equations say that the internal state f results from the system H and the sum of processed inputs. The output y depends on the sum of the processed state *and* inputs.

For example, consider a TV set with less than ideal reception. Separate out your hand and the fine-tuning knob (plus associated circuit). The resulting input is $B(t)g_1(t)$. The antenna brings in $A(t)g_0(t)$. Here $A(t)$ is determined by the antenna, $g_0(t)$ by the TV station. Likewise, $g_1(t)$ could be the rotation angle of the knob and $B(t)$ the fine-tuning circuitry. The signal delivered to the lens system could be $f(t)$, and the pattern on the cathode ray tube $y(t)$.

If the picture is unsatisfactory, you will probably change the knob angle g_1. You may wonder how to design an automatic control g_1 which would continually respond to variations in g_0 so as to improve the picture.

How then to solve the equations? One method is to take Fourier transforms, for these focus on essentials of the signals g_0, g_1, f, and y. The Fourier transform of $H(t)f(t)$ can be written as $\hat{H}(\omega)\hat{f}(\omega)$. Here $H(\omega)$ is a complex-valued function of frequency ω called the system transfer function, and $\hat{f}(\omega)$ is the Fourier transform of f. The system equations (1) and (2) can be transformed into algebraic equations for $\hat{f}(\omega)$ and $\hat{y}(\omega)$. If we translate our requirements on the output y into $\hat{y}$, and so into requirements on $\hat{g}_1$ (for known $\hat{g}_0$), we can then choose $\hat{g}_1$ suitably. If there is a desired output level $z(t)$, we can try to minimize $z - y$ (or $\hat{z} - \hat{y}$) in some sense. The absolute value $r(\omega) = |\hat{y}(\omega)|$ and the phase angle $\theta(\omega)$—defined by $\hat{y}(\omega) = r(\omega) \exp i\theta(\omega)$—are often used to specify $y(\omega)$.

This reduction of $y(t)$ into $r(\omega)$ is behind the practical design methods attached (in the United States) to the names Nyquist, Bode, Evans, and Nichols. Each of them graphed different functions of r and θ against ω or k log ω, and determined designs from these graphs. The same methods are known in Europe under other names.

Important phrases in control theory are "open-loop," "closed-loop," and feedback." Actually, they are somewhat dependent on context. In the context of the above equation system, the control $g_1(t)$ is open-loop if determined by the desired output $z(t')$ for any or all times t', but not by the actual output y. It is closed-loop if determined by $y(t'')$ for $t'' < t$, or by $z(t')$ and $y(t'')$ for $t'' < t$. It is feedback if determined by more or less current values of $y(t'')$, or of $z(t')$ and $y(t'')$. Obviously, other control types are possible. The open-loop $z(t')$ information could be restricted to times $t' < t$, or to current values of t', and so on. Many writers

identify closed-loop with feedback, but the present capability of electronic systems allows the open loop to be closed with weighted integrals over $y(t'')$ for $t'' < t$. This is not allowed in most feedback discussions. Some writers also require an explicit measurement of $y(t)$ for "authentic" feedback.

Optimal Design

The theoretical possibility of optimal controls is implicit in the classical controls. However, the applications before 1940—cars, ships, airplanes, radio amplifiers, and monorails—were rather forgiving of sloppy performance. The seriousness of the problem of air defense became obvious with the German bombing and strafing of Spain and Poland in the 1930s. Radar gun control in principle would be sufficient, but filtering of the noisy radar data, prediction from the filtered data, and good control of the gun platform were all needed for successful operation. Helicopters were then notoriously unstable. Many World War II weapon systems seemed to be pressing against the limits of classical control. A natural outcome was the desire to push control as far as technically possible, regardless of expense.

The first actual example of an optimal control was Bushaw's 1952 "bang-bang" solution to the problem of extinction of the harmonic oscillator. The objective is to find a control input $g_1(t)$ such that the solution f to the equation $\ddot{f} + \omega^2 f = g_1$ tends to zero in the minimum time. The answer is to switch $g_1(t)$ from $+k$ to $-k$ at a sequence of times t_0, $t_0 + 2\pi/\omega$, $t_0 + 4\pi/\omega$, ... This resembles the optimal solution to the age-old problem of navigating a sailboat against a constant wind. As any sailor might suppose, the solution is periodic tacking. Zermelo proved this and found the period.

These solutions are philosophically interesting, since g_1 is discontinuous, though f_0 and f are continuous. They are also quite simple and fairly practical to implement, provided we can neglect the control signal variation during and just after the switching process.

Discrete control settings such as *+1* and *-1*, or *full*, *3/4*, *1/2*, *1/4*, *0*, *-1/4* (speeds), have long been familiar. The fact that they might be optimal came as somewhat of a surprise. Of course, continuous optimal controls may be usefully approximated by discrete ones. Good switching-time rules are hard to find, however.

The theory of optimal control is a chapter of the calculus of variations, an outgrowth of ordinary calculus. The roots of optimal control go back at least to the German mathematician Mayer, the

British physicists Airy, Maxwell, and Routh, and the Russian scientist Vyshnegradskii in the nineteenth century. Between 1940 and 1960, world-famous mathematicians studied both general and special control problems. We mention only the Americans Wiener, McShane, Bushaw, and Bellman, the Russians Kolmogoroff, Pontryagin, and Gamkrelidze, and the Frenchman Lions. The most convenient approach to special problems was made by Rudolf Kalman and was set out between 1958 and 1962. One advantage of Kalman's formulation is the ease of reaching back into the design stage to improve the system performance. Not all problems of optimal control are best handled by Kalman's approach. Bellman's optimization principle–that a section of an optimal path is optimal for that section–is sometimes very useful, as well as insightful.

Physical Applications

The applications of optimal control are extremely diverse. We begin with a problem of more than historical interest, put by the American rocket pioneer R. H. Goddard in the 1920s. Suppose a sounding rocket is to climb vertically against an air resistance profile (given as a function of velocity and height) and a gravitational pull. How should the "gas pedal" be varied in order to reach the maximum height, given a fixed fuel supply? A simplified solution, which takes into account the changing mass of the rocket, was given by the German, Miele, in 1926. A more realistic analysis was given by Dr. W. R. Haseltine of the NWC Mathematics Division and Professor G. M. Ewing. Somewhat surprisingly, the optimal solution contains periods of zero fuel outlay (coasting). Most optimal controls have nonintuitive aspects, one reason perhaps for their slow acceptance in some circles. This is because our minds are not quite structured to wrap around the more complicated physical systems. In explaining optimal controls, we often try to find a version of the problem which makes the solution at least *seem* intuitive.

Another difficult control problem tackled by Dr. Haseltine is the design and tuning of nutation (wobble) dampers for rotating bodies. A damper invented by H. L. Newkirk of NWC and analyzed by Dr. Haseltine was used to stabilize the attitude of NASA space satellites. More recently Dr. H. A. Wilcox, Senior Technical Consultant for NWC, and Dr. Haseltine have turned their attention to damping the wobble in high-performance gyroscopic seekers for advanced missiles by adding suitable mechanical elements. Their solutions are based on particular types of physical apparatus, but are optimal within the type.

More typical of current problems is the use of optimal controls in the electronic sections of control svstems. also studied by Dr. Haseltine. Kalman's approach provides optimal feedback control equations, the so-called Matrix Riccati Equations, when the performance index is quadratic and the system is linear. The solution of these quadratic matrix differential equations tends to be tedious. Even the steady state, given by quadratic matrix *algebraic* equations is time-consuming on the largest electronic computers. Dr. G. A. Hewer of NWC has investigated computer algorithms for lightening this task. Dr. Hewer has also considered the theory of optimal controls in periodically varying systems, such as appear in parametric amplifiers. Such work may well be relevant to cardiac-assist devices and to economic control systems, for instance, the agricultural sector of the economy, which has many periodic components.

Mechanical systems are affected by friction, both viscous (fluid) and coulomb (solid or dry). Viscous friction is often introduced deliberately to damp vibrations or to lubricate dry surfaces. Dry friction is nearly always a result of inexpensive design. To eliminate it completely requires levitation—a difficult solution. Fluid lubrication is not always desirable—as at low temperatures—or practical. Bearings and surface treatment, such as polishing, hardening, and crystal deposition, reduce friction but do not eliminate it. The physics of dry friction are difficult to handle in oscillatory physical systems from the mathematical and computing aspects.

Drs. Haseltine, Hewer, and R. B. Leipnik have been studying several models of dry friction in their bearing on control theory. Results of these studies are relevant to certain electronic controls as well. (The mathematical aspects of dry friction—dead zones, discontinuity, and saturation—are found in many electronic components, such as diodes and transistors.) Computer runs show that, while friction produces incredibly complex motions in otherwise simple systems, inner and outer boundaries for most nonresonant motions are relatively simple. Optimal controls for minimum time are modified "bang-bang," as expected.

Encounter Problems

Control problems often involve an encounter. This can be *unilateral*, as in docking a ship or landing a plane. It can also be *cooperative*, as in docking two spaceships or refueling planes in flight. Obviously, the meeting can be *combative*, as in actions between military adversaries. Traditional optimal control theory applies directly only to unilateral encounters. Substantial modifications are required for the cooperative or combative encounters. At

NWC the missile design task involves the discovery and use of "guidance laws" for the destruction of both fixed and mobile targets on the earth or in the sea or sky. However, the nature of evasive or counteractive measures must be analyzed to some extent. Control theory can then be applied to find guidance laws.

A natural approach to the combat problem is to make one side the pursuer and the other the evader throughout an engagement. More realistic is to assume that the pursuit initiative will change hands, perhaps repeatedly, as the situation develops. The tactics of the adversaries can be partially based on experience, if there is some. Tactics for one side can, however, be calculated by the use of optimal control, provided that the other side uses a definite sequence of tactics. This has been done for NWC air-to-air missiles by Dr. E. W. Mikami of the Mathematics Division. He used Courant's penalty function technique, as developed by Professor Balakrishnan. Penalty functions permit realistic differential equations of motion of the adversaries to be taken into account without being solved. This idea greatly reduces the amount of computing, as compared with the traditional explicit method.

In this connection, we can see the weaknesses and strengths of optimal control. The optimal guidance law is usually too complicated to be kept in mind by a pilot—or in memory by a small computer—and is not necessarily of the easily implemented feedback type. It does provide a standard by which simpler guidance laws may be judged. On the other hand, good performance in several respects is often more important than peak performance on a single standard. To some extent this can be accommodated in Kalman's theory by inclusion of several terms in the performance index and by varying their weights. The choice of weights should be related to the sensitivity of the results to likely variations in initial conditions and other parameters. This is one arena in which engineering judgment is exercised. Generally, an optimal feedback law can be obtained for a quadratic performance index, as mentioned earlier. The *proportional navigation* law is a simple and fairly effective form of feedback guidance. *Pursuit navigation* is still simpler, but not as effective. When targets maneuver rapidly, neither of these sight-line laws works very well. More information about the motion then becomes necessary.

The ideas described above apply directly when tracking is accurate and well centered. The shifting—generally late in flight—of missile attention from one part of a target to another may be accidental or deliberate. In either case, it has a large effect on the final phases of the encounter. A guided missile contains many correlated servo

loops through which signals flow. Proper cascading of this signal flow helps to keep lock-on. Computer studies by H. N. Browne of NWC have uncovered some of the principles involved, but optimal shifting of control has not yet been achieved.

A more sophisticated analysis of combat may be based on Von Neumann's Theory of Games. When the tactics can be continuously modified and are constrained by the differential equations of motion, we speak of *differential games.* So far, only the simplest types of differential games have lent themselves to practical computing. Some Navy problems will doubtless be approachable by this method in the next five years, but air combat is probably not among them. Nevertheless, contact is maintained at NWC with differential game theory and the related fields of infinite dimensional linear programming and fixed points of set-valued mappings. F. C. Reed of NWC has also studied the optimal control of queues (waiting lines) in a doctoral thesis at Stanford. The application to firing policy in multiple encounters is immediate. An unusual control problem which Reed has taken up in a medical journal is the time of delivery of erythroblastotic (Rh-incompatible) babies. As pregnancy continues, the level of Rh risk statistically increases while other risks clearly decrease. Given the Rh situation—which can be monitored in the fetal stage—an optimal time of delivery can be estimated.

Applications to Large-Scale Problems

Optimal control and games theory can also be applied to storage and transport logistics. A simple example is the material shipment problem studied by Hitchcock and Koopmans in 1944, the beginning of linear programming in the western world. More difficult by far is the optimal control of aircraft and tracked rapid transit vehicles, taking into account the periodically varying passenger flow and the requirement to avoid collision and jolting. We hope to study this problem—a natural example of variable-load logistics. This can be viewed as a contribution to the NWC effort in transfer of technology to the civil sector, as Reed's medical study.

Large engineering projects in the United States are usually divided among many groups, each of which designs a particular subsystem. The final "design integration" phase requires reconciling the various subsystems with suitable interfacing blocks and eliminating unhelpful cross effects. This often neglected phase can be frustrating and difficult. Can control theory be of assistance here? We believe that it can through designing the interfacing blocks directly from the

subsystems. The same methods are applicable to more diffuse systems, such as national power grids and their inter-ties.

The range of applications of control theory at NWC is far wider than that indicated above. Good accounts of the theory and the techniques of this fast-developing subject are found in *Theory of Non-Linear Control Systems* by the noted Navy scientist N. Minorsky, and *Applied Optimal Control* by A. Bryson and Y. C. Ho. *The Origins of Feedback Control* by O. Mayr carries the story from Ctesibos' float valve of 300 B.C. through Watt's centrifugal governor to Breguet's clock synchronizer of 1793.

Anechoic Chamber for acoustic research at NWC

U. S. GOVERNMENT PRINTING OFFICE : 1974 O - 539-665

View of the Cosa Range

NAVAL RESEARCH REVIEWS publishes highlights of research conducted by Navy laboratories and contractors and describes important Naval experimental facilities. Manuscripts submitted for publication, correspondence concerning prospective articles, and changes of address, should be directed to Code 109, Office of Naval Research, Arlington, Va. 22217. Requests for subscriptions should be directed to the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Subscription price: $4.50 per year in the U.S. and Canada; $5.65 per year, foreign; $0.45 per individual copy. The issuance of this periodical approved in accordance with Dept. of the Navy publications and printing regulations.

Editor: WILLIAM J. LESCURE

Associate Editors:

A. R. LAUFER, ONR PASADENA

A. R. DAWE, ONR CHICAGO

A. L. POWELL, ONR BOSTON

D. A. PATTERSON, NAVAL RESEARCH LABORATORY

NAVSO P-510

IN THIS ISSUE

VOL. XXVII, NO. 3

The Naval Weapons Center—A Multifaceted Research and Development Environment ..... ELIZABETH BABCOCK 1

The Center is the principle Navy RDT&E center for air warfare and missile weapon systems.

Dividends of Dye Laser Research ..... RICHARD S. HUGHS 17

The Center initiated a research program to investigate the potential of the tunable dye laser in 1969. This program has put fluorescence, a phenomenon of nature, to work in a new way.

Improvement of Mirror Surfaces ..... JEAN BENNETT 29

The mirrors that will be used in the new high-energy laser systems have stringent requirements; they must reflect maximum light specularly.

Optimal and Classical Controls ..... R. B. LEIPNIK AND G. A. HEWER 36

Several groups at the Center have been studying control problems of present and future Navy systems.

Cover Caption

Artist's concept of activities at the Naval Weapons Center.

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
ARLINGTON, VA. 22217

OFFICIAL BUSINESS

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY
DoD-316

U.S.MAIL

PENALTY FOR PRIVATE USE, $300.